Australian Government
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Radio Frequency Signal Propagation Study

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ABSTRACT

This investigation aims to determine how ground to ground L-Band signals propagated in the Woomera region behave, as well as which propagation model best represents measured results.

The results were split into two scenarios depending on the variables tested. The two scenarios were analysed separately due to their differences in equipment setup. For each scenario the best fitting model was determined and then the two scenarios would be compared based on model performance.

Overall, the Advanced Refractive Effects Prediction System (AREPS) was the best fit 60 % of the time. The modelled propagation loss was within 22 – 26 dB of the measured value 95 % of the time. The Free Space model which is usually the 'back of the envelope' calculation was never the best fit for the data. However, the results indicate that if a back of the envelope calculation is required, the two-ray ground reflection model is a much better choice than Free Space, although it still appears to consistently underestimate ground-to-ground propagation losses.

RELEASE LIMITATION

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Radio Frequency Signal Propagation Study

Executive Summary

Throughout DSTO, trials are often conducted at the Woomera Test Range or in the greater Woomera area due to its remote location. This investigation aims to determine how ground to ground L-Band signals propagated in the region behave over a range of distances, frequencies, polarisations and antenna heights.

The results were split into two scenarios depending on the variables tested. The two scenarios were analysed separately due to their differences. For each scenario the best fitting model was determined and then the two scenarios would be compared based on model performance.

Scenario 1 looked at varying transmitter heights, frequencies, polarisations and distances between transmitter and receiver. The data was grouped according to variables and a model was selected as the best fit based on the Root Mean Square (RMS) value of the difference between model predictions and measured data. The model that had the most occurrences of being the best fit across all variable groups was the Advanced Refractive Effects Prediction System (AREPS) model. This occurred 69 % of the time. 95 % of the time, AREPS was within 26 - 30 dB of the measured data.

Scenario 2 looked at a more specific soldier versus soldier situation. The transmitter height was constant, and the receiver height varied to simulate ground operations. There was only one polarisation and the same frequencies in scenario 1 were used. The same data analysis approach for scenario 1 was used with the result being that AREPS was the model with the most occurrences of being the best fit. This occurred 37 % of the time. 95 % of the time, AREPS was within 14 - 18 dB of the measured data.

Combining both scenarios, AREPS was the best fit 60 % of the time. 95 % of the time AREPS was within 22 - 26 dB of the measured data. The model with the second highest occurrences of being the best fit was the Parabolic Equation Model (PEM) model. This occurred 21 % in scenario 1, 32 % in scenario 2 and 24 % overall. The 95 % confidence intervals for the PEM model were 34 - 38 dB in scenario 1, 17 - 21 dB in scenario 2 and 30 - 34 dB overall.

The Free Space model which is usually the 'back of the envelope' calculation was never the best fit for the data. This model underestimated the measured power loss in all tests done by as much as 65 - 69 dB. This model underestimated the power loss least at closer range and higher transmitter heights, as would be expected. However, the results indicate that if a simple back of the envelope calculation is required, the Two-Ray Ground Reflection model is a much better choice than Free Space, although it still appears to consistently underestimate ground-to-ground propagation losses.

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Elizabeth Smith graduated from the University of Newcastle in 2009, completing a Bachelor of Science (Honours) majoring in Physics. In 2010, she worked as part of the Ionospheric Prediction Service at the Bureau of Meteorology in Sydney where she worked on the effects of solar flares on Australia's power networks. In 2011 she joined DSTO through the graduate program as part of the Assured Position, Navigation and Timing group (formerly Global Navigation Satellite Systems group). Her work has ranged from GPS receiver testing and data analysis to conducting trials to determine signal propagation loss in the Woomera region.

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1. Introduction

Throughout Defence Science and Technology Organisation (DSTO) trials are often conducted at the Woomera Test Range or in the greater Woomera area due to its remote location. Participants transmitting and receiving in the area are required to understand how their signals will change over distance under different conditions.

This investigation aims to determine how ground to ground L-Band signals propagated in the Woomera area behave over a range of distances, frequencies (from 1.2 to 1.7 GHz), polarisations and transmitter / receiver heights. The results will be compared to various propagation models to determine which best represents the observed data.

The trial was conducted with the help of Chris Baker, Mark Knight and Chris Pitcher, all members of the Assured Position, Navigation and Timing (APNT) group in CEWD at DSTO.

Section 1 details the background to this investigation including previous trial experiences. It also details the models used in this investigation. Section 2 outlines the equipment used in the experiment, how and why it was set up. Section 3 details how the experiment was conducted, what variables were tested, and in what combinations. The results of these tests are given in Section 4 with a comparison between measured values and the models described in Section 1.2. How this investigation can be improved and extended will be explained in Section 5.

1.1 Background

During previous trials at Woomera, it appeared that the signal power loss during propagation was significantly higher than the models used to predict it would suggest.

When in the field, the free space and 2-ray ground reflection models (described in Sections 1.2.1 and 1.2.2 respectively) have been used to estimate the signal power loss over a given range. They were used mainly due to their simplicity and can be used anywhere without a complex modeling program.

It has been postulated that the soil conductivities at Woomera are affecting the signal propagation. The soil in the area is usually dry, rocky, sandy (see Figure 1) and quite different to that of coastal areas. A more detailed description of the area is given in Section 1.3.

To determine if there is a significant difference in signal propagation in this area, a series of signal propagation tests was conducted. The results were compared to the models described in Section 1.2 to determine how accurate the simple equations are compared with more involved models.

Figure 1: Landscape in Woomera. The soil is dry, rocky and sandy with small shrubs and grasses

1.2   Propagation Models

There are a wide range of radio frequency signal propagation models varying in complexity and accuracy. For this experiment the simplest and most commonly used models were selected as well as some models primarily used by the military forces around the world. Following is a brief description of the models used.

1.2.1   Free Space

The free space propagation model applies to situations where the transmitter and receiver are within line of sight and the propagation path is free from obstacles. The free space propagation model applies for propagation in a vacuum; however, the model may be reasonably accurate for air-to-ground and ground-to-air transmissions.

The model is described by equation 1.

$$L_P = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right)dB$$

Equation 1: Free Space signal propagation equation

Where:

L_P = Signal power loss (dB)
R = Range between transmitter and receiver (meters)
λ = Wavelength of the signal being transmitted (meters)

The wavelength term arises due to the frequency dependence of the receiving antenna and not as a result of free-space propagation [5].

The free space model is usually used as a simple, back of the envelope calculation to determine an estimate of signal power loss over a given distance. However, as the transmitter and receiver approach the Earth's surface in height, the reflections from and conductivities of the ground begin to affect the signal propagation [8]. This is when the 2-ray ground reflection model becomes more appropriate.

1.2.2   2-ray Ground Reflection Model

The 2-ray ground reflection model used in this experiment assumes a simple flat earth and that the received signal is a combination of two signals. A direct line of sight signal combined with one reflected signal from the ground. The equation used to calculate the propagation loss is given in equation 2[9].

$$L_P = 20 \log_{10} \left(\frac{R^2}{h_T h_R} \right) dB$$

Equation 2: Ground Reflection propagation equation

Where:

L_P = Signal power loss (dB)
R = Distance between transmitter and receiver (meters)
H_T = Height of the transmitter (meters)
H_R = Height of the receiver (meters)

This model only applies when the propagation distance is greater than the turnover distance, R_0 described in equation 3[9].

$$R_0 = \frac{4 h_T h_R}{\lambda}$$

Equation 3: The Ground Reflection model is only valid for distances greater than the turnover distance, R_0

If the propagation distance is shorter than the turnover distance, then the propagation is more accurately modelled as a direct and reflected ray which gives rise to constructive and destructive interference zones and the ground-reflection model becomes inaccurate.

The ground reflection model includes range to the fourth power compared to the free space model which only includes the square of the range. At shorter ranges, the free space model can be more accurate than the ground reflection model, due to the turnover distance and multipath issues.

1.2.3   Parabolic Equation Model (PEM) in Matlab

In general, the parabolic equation model is an approximation of the wave equation which represents energy propagation in one main direction. The model can be changed to include varying degrees of complexity and variables. It has the capacity to include digital terrain elevation data (DTED) and other environmental effects as well as transmission details, such as antenna heights, frequency and polarisation. The model allows the calculated propagation loss to be determined as a function of these variables. Unlike the ground reflection and free space models, the PEM is frequency dependent as seen in equation 4[2].

$$\frac{\partial^2 u}{\partial z^2} + 2ik\frac{\partial u}{\partial x} + k^2(m^2(x,z)-1)u = 0$$

Equation 4: Form of the Parabolic Equation Model (PEM)

Where:

$u(x,z)$ = amplitude or attenuation function. Represents the slow phase variance in the horizontal direction
$m(x,z)$ = modified refractive index which accounts for the Earth's curvature
x = range
z = height
$i = \sqrt{-1}$ the imaginary component for the phase of the wave
k = wave number in vacuum given by $k = \dfrac{2\pi}{\lambda}$

The specific PEM used for this experiment was developed by DSTO personnel in Matlab [7] (shown in Figure 2). It is an incomplete version which is intended to eventually be capable of full 3D propagation modelling.
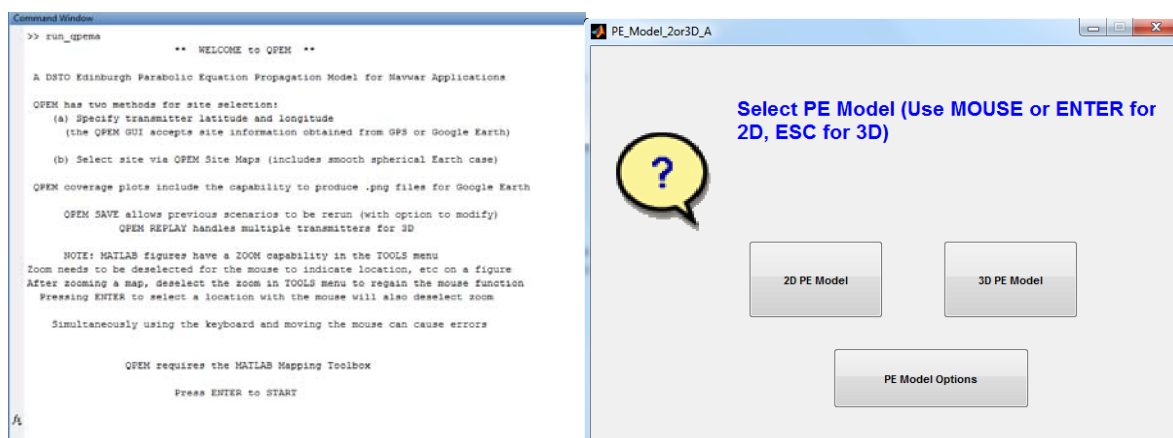

Figure 2: Parabolic Equation Model (PEM) written by DSTO personnel in Matlab. On the left is the start up screen in Matlab, on the right is the program running, giving the options of a 2D or 3D model.

1.2.4 Advanced Refractive Effects Prediction System (AREPS)

The AREPS program designed by SPAWAR incorporates several propagation models including the Parameterized Ionospheric Model (PIM), the International Reference Ionosphere model and the Advanced Propagation Model (APM)[10]. The model used in the program depends on the frequency and scenario selected.

The AREPS program allows several characteristics of the scenario to be modelled, such as ionospheric effects, atmosphere type, ground type etc. Like the PEM it can incorporate any level of DTED data to improve the performance of the program and is frequency dependent. When creating a scenario, input parameters such as signal frequency, antenna characteristics (type, polarisation and height) as well as environmental factors are needed.

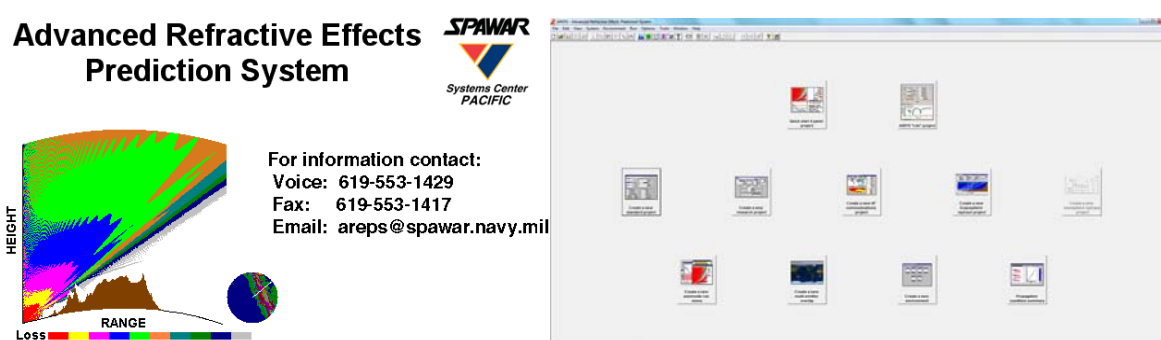During the testing reported here, the program AREPS 3.0 was used (Figure 3).

Figure 3: Screen shot of Advanced Refractive Effects Prediction System (AREPS) modelling program. On the left is the details of the program and on the right is the start up menu where you can select what type of scenario you would like to begin.

1.2.5 GPS Interference and Navigation Tool (GIANT)

GIANT is a program developed by LinQuest[1] designed to facilitate mission planning by calculating the GPS effects in varying scenarios [3]. It incorporates the possibility of disrupting the GPS signals from either hostile forces or simulated satellite error.

As with PEM and AREPS, GIANT can include DTED data to enhance the outcomes of the model. When DTED data is used, the program uses the Terrain Integrated Rough Earth Model (TIREM) to calculate the signal propagation loss of jammers. If there is no DTED data available, the program uses the Spherical Earth Model (SEM) to calculate propagation loss. In this model a single ground height is used. [4]

As the program is designed inherently for mission planning, using the program to determine signal power loss over a given distance is a minor challenge. The program has such a great

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[1] LinQuest provide government and private industries with technical and software solutions

number of variables to select including the waveform used and whether the platform is moving.

For the results displayed in this report, GIANT 4.4.4.189 was used (Figure 4). This version of the program does not allow frequencies other than L1 (1575.42 MHz) and L2 (1227.6 MHz) to be simulated. However, as the frequency dependence of the propagation loss over most scenarios in Chapter 4 is small, then comparison with measured propagation loss at different frequencies is still useful in order to test the accuracy of this model.
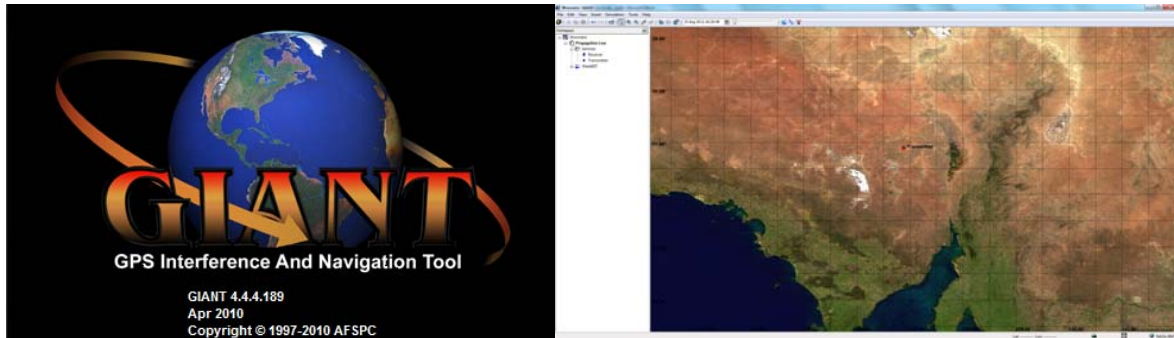

Figure 4: Screen shot of GPS Interference And Navigation Tool (GIANT). On the left is the details of the program and on the right is the main operating window.

1.3   Environment

The Woomera town is 488 km North of Adelaide in South Australia. To the North-West of the town is the Woomera Prohibited Area (WPA). This area is used by both civilians and military personnel.

The landscape consists of a mostly dry red soil with some rocky areas and small bushes (see Figure 1). The terrain appears deceptively flat however it contains a lot of slight hills and depressions.

The weather in the region is mostly dry and warm during the day with night temperatures dropping significantly. The area is prone to strong winds which can cause dust storms.

Nearby to the testing sites were large power lines (Figure 5). The testing was adjusted so that signal paths never crossed the power lines as this could have affected the signals.
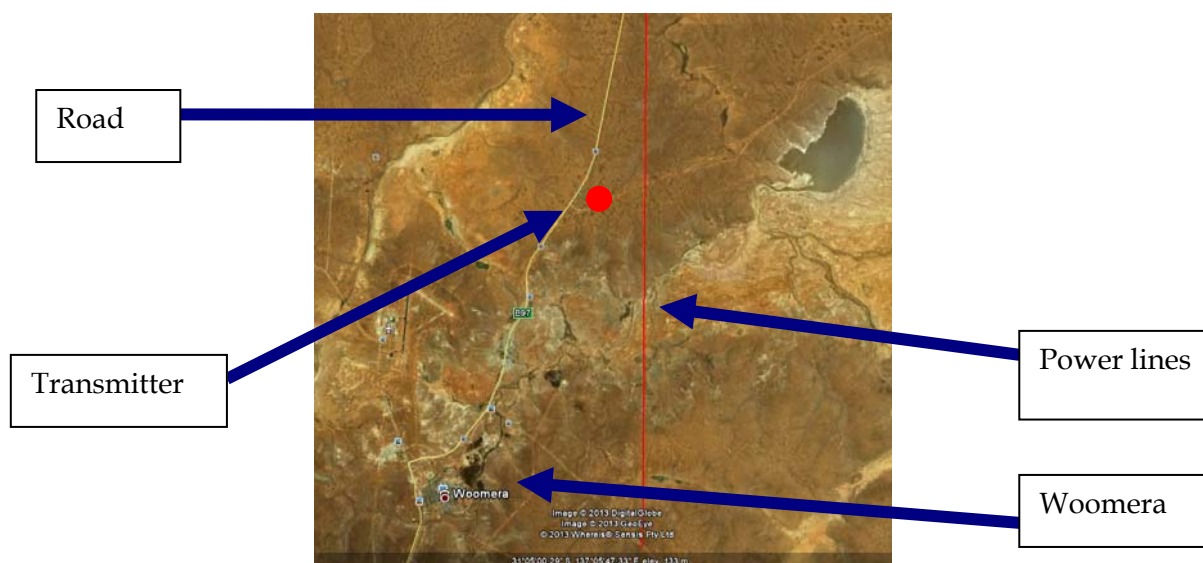
Figure 5: Location of the transmitter site with respect to Woomera, the road, and the power lines

2. Equipment and Setup

2.1 Trial Location

The area used for testing was located on Arcoona Station, around 15 minutes drive north of the Woomera town. The site allowed for setup of equipment off the main road to minimise risks to the participants. As the trial activity was unclassified, a site off-range was chosen to eliminate the need to obtain range approval. The Woomera Testing Range was, however, notified of the activity and frequencies used to prevent any potential impact to range users (note that signals were not transmitted at the GPS frequencies). The terrain was considered to be representative of that encountered on the range. Arcoona Station was notified in advance of the trial.

2.2 Transmitter Site

It was decided to keep the transmitter in one place to minimise errors in position and distance. The site consisted of a pump up mast with either a helix or horn antenna mounted (see Figure 6). A smaller tripod was also used at the transmit site (Figure 7).

Figure 6: Transmitter site with a horn antenna mounted on a pump up mast for Scenario 1

Figure 7: Transmitter site with a helix antenna mounted on a tripod for Scenario 2

There was a signal generator at the transmitter site from which the signal was passed through an amplifier. The signal was split to allow for a spectrum analyser to ensure the power levels produced by the signal generator were correct. This also allowed us to determine that the power levels and frequencies did not drift due to variations in temperature. The other path from the splitter went to the transmitting antenna (shown in Figure 8). The details of the equipment used at the transmitter site are given in Table 1.
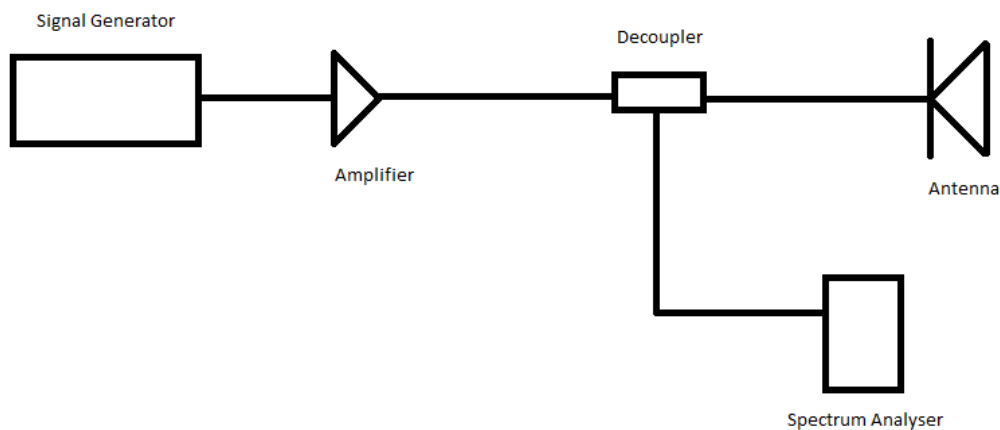
Figure 8: Equipment setup for the transmitter site. The signal generator sent the signal through an amplifier to a directional coupler where the signal was split to a spectrum analyser and the transmitting antenna.

Table 1: Details of the equipment used at the transmitter site

Equipment	Details
Signal Generator	VICOM 2023B 9 kHz – 2.05 GHz
Amplifier	Aethercom S/N 234
Directional Coupler	Rojone AMA-1255-30-1W, 30 dB
Spectrum Analyser	R&S FSH 4, 9 kHz - 3.6 GHz
Horn Antenna	L-Band 15.2 – 17.6 dBi gain, approx 28˚(L1)/ 40˚(L2) beamwidth – purpose built by DSTO
Helix Antenna	L-Band 9.4 – 11.6 dBi gain, approx 34˚(L1)/ 50˚(L2) beamwidth - purpose built by DSTO

2.3   Receiver Site

The receiver sites were moved according to the distance required for testing. The positions were not in a continuous bearing from the transmitter due to the need for access by a road. The terrain for the setup needed to be relatively flat to allow for 0 degrees inclination of the antenna, as well as stability for the tripod (Figure 9).

The signal received by the antenna was run into a handheld spectrum analyser (Figure 10). The signal path is shown in Figure 11 and the details of the equipment used are given in Table 2.

Figure 9: Receiver site with a horn antenna mounted on a tripod for both Scenario 1 and 2
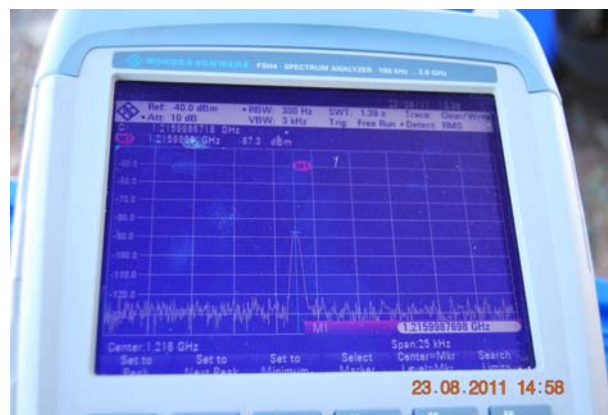

Figure 10: The received signal viewed on the spectrum analyser. The peak power is recorded and compared to the transmitted power measured at the transmission site to determine signal power loss.

All locations were measured with a handheld Garmin GPS receiver. The compass / bearing function was used to determine line of sight to the transmitting antenna in order to align the

transmitting and receiving antennas. The bearing only needed to be determined within a 5˚ accuracy due to the beamwidth of the antennas, which was easily achieved with this method.
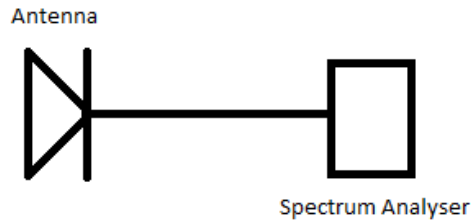

Figure 11: Signal path from the receiving antenna to the spectrum analyser

Table 2: Model and serial numbers for the equipment used at the receiving site

Equipment	Model / Serial Number
Spectrum Analyser	R&S FSH 4, 9 kHz - 3.6 GHz
Horn Antenna	L-Band 15.2 – 17.6 dBi gain, approx 28˚(L1)/ 40˚(L2) beamwidth – purpose built by DSTO
Helix Antenna	L-Band 9.4 – 11.6 dBi gain, approx 34˚(L1)/ 50˚(L2) beamwidth - purpose built by DSTO

3. Experiment

3.1 Scenario 1

Scenario 1 was set up to determine the effects of polarisation, transmitter height, range and frequency on signal propagation loss. Three distances were tested, up to a range of 5 km. The locations of the transmitter and receiver sites are shown in Table 3. The location of the receiver sites with respect to the transmitter site can be seen in Figure 12. The green line shows the signal path between transmitter and receiver.

Table 3: Latitude and Longitudinal coordinates of the transmitting and receiving sites for Scenario 1

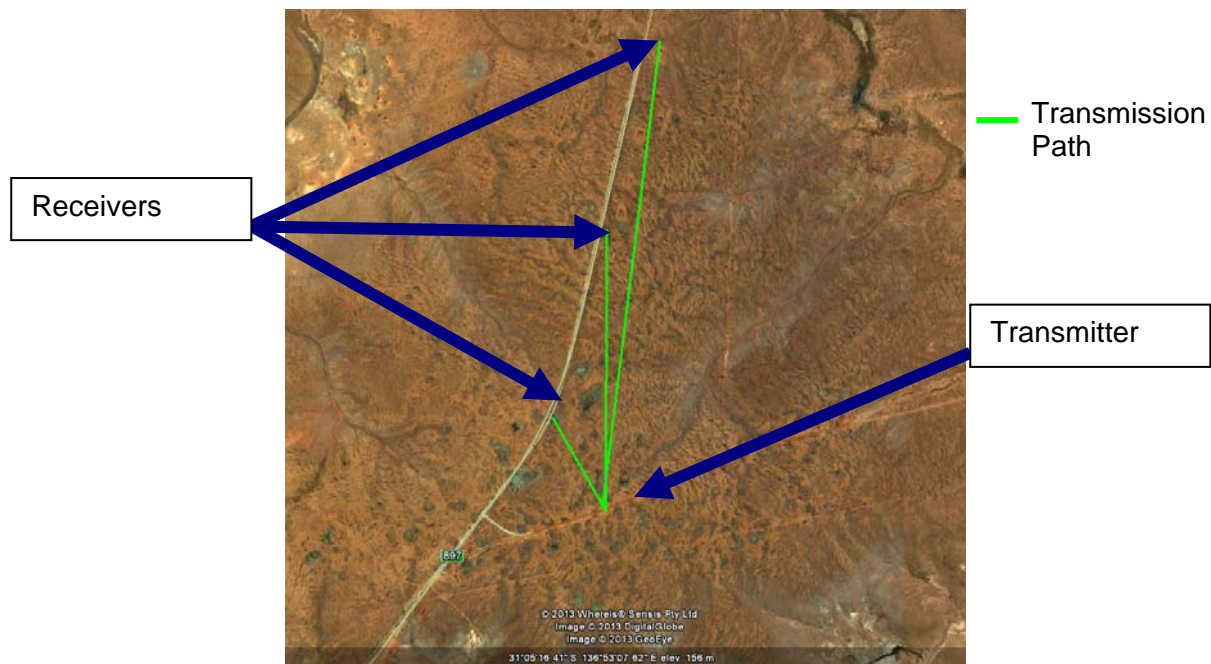| Site	Latitude	Longitude
Transmitter	31º 06' 40.1" S	136º 53' 04.6" E
Receiver @ 1.18 km	31º 06' 07.2" S	136º 52' 42.2" E
Receiver @ 3.06 km	31º 05' 01.4" S	136º 53' 02.1" E
Receiver @ 4.98 km	31º 03' 59.9" S	136º 53' 21.6" E

Figure 12: Transmission paths for the three different ranges tested in Scenario 1. The transmitter was kept stationary, and the receiving location was moved along the road.

Transmission licences for the following five frequencies were obtained, 1216, 1270, 1399, 1525 and 1650 MHz. These frequencies were chosen as they are close to the L1 (1575.42 MHz) and L2 (1227.6 MHz) GPS frequencies. The actual GPS frequencies weren't used as doing so could disrupt GPS for any users in the area.

Three polarisations of antennas were used in difference configurations. An L-Band horn antenna was used which can be orientated to generate and receive a vertically or horizontally polarised signal, and a helix antenna which can generate a circularly polarised signal. The horns were set up to have either matching polarisations (e.g. both vertically polarised) or cross polarisation (transmit on vertical, receive horizontally). The polarisation combinations used were:
- Vertical to vertical
- Horizontal to horizontal
- Circular to circular
- Cross Polarised (Horizontal to vertical or vertical to horizontal)

The transmitting antenna was connected to a pump up mast (seen in Figure 6) whose height could be adjusted. The bearing on the antenna was set whilst it was low to the ground. The bearing accuracy only needed to be within 5° due to the beamwidth of both antennas. The orientation of the antenna may change slightly with the raising of the mast and wind effects; however the beamwidth is large enough to compensate for these errors.

Three heights were chosen to give a representative sample of the effects of varying transmitting height. The heights were 3.43 m, 6.13 m and 8.93 m. The height was measured

from the ground to the centre of the transmitting antenna. The receiving antenna was set at a constant height of 1.9 m.

At each transmitter height, all five frequencies and four polarisation combinations were tested for each range shown in Table 3 (a total of 180 measurements). The transmitted power was measured on a spectrum analyser at the transmitter site and recorded. The received power was measured on another spectrum analyser at the receive site and recorded. Post trial, the antenna gains, cable losses and signal generator calibrations were taken into account to calculate just the signal power loss between antennae as demonstrated by equation 5.

$$L_P = ERP - P_R - G_{RA} + L_C$$

Equation 5: Signal power loss between transmitting and receiving antennas

Where ERP is the Effective Radiated Power shown in equation 6:

$$ERP = P_T + G_{TA} - L_C$$

Equation 6: Effective Radiated Power (ERP) of a transmitter

P_T & P_R – The measured transmitting and receiving powers
G_{TA} & G_{RA} – The transmitting and receiving antenna gain
L_C – Cable loss measured on a network analyser

The L_P values calculated are the measured values used in Section four in comparison with the propagation models described in Section one.

3.2   Scenario 2

Scenario two was designed to simulate a soldier in the field, walking or driving with a handheld receiver being interfered with by a handheld jammer. This was done using only circularly polarised signals, as this would be more likely in a real situation.

The receiver heights were varied to simulate ground operations e.g. dismounted soldier, land vehicle etc. The three receiver heights were 1.2 m, 2 m, and 3 m approximately. The transmitter was kept constantly at a height of 1.9 m but always directed towards the receiver.

The five frequencies mentioned in Section 3.1 were used across the ranges listed in Table 4. The direction of the transmissions is shown in Figure 13.

The determination of the signal power loss is the same process as described in Section 3.1.

Table 4: Latitude and Longitudinal coordinates of the transmitting and receiving sites in Scenario 2

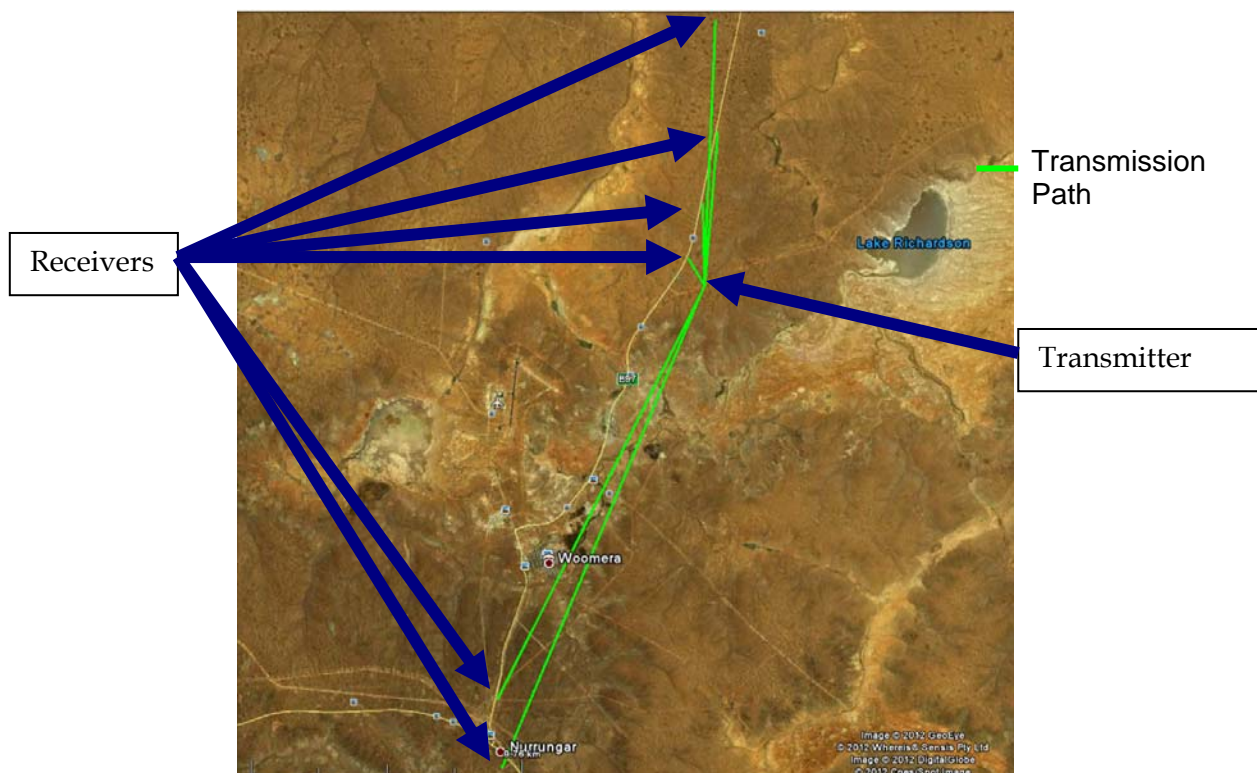| Site	Latitude	Longitude
Transmitter	31º 06′ 40.1″ S	136º 53′ 04.6″ E
Receiver @ 1.14 km	31º 06′ 09.2″ S	136º 52′ 41.3″ E
Receiver @ 2.99 km	31º 05′ 03.5″ S	136º 53′ 01.9″ E
Receiver @ 5.61 km	31º 03′ 40.0″ S	136º 53′ 22.4″ E
Receiver @ 9.62 km	31º 01′ 30.9″ S	136º 53′ 41.0″ E
Receiver @ 16.63 km	31º 14′ 41.2″ S	136º 48′ 23.1″ E
Receiver @ 18.73 km	31º 16′ 01.1″ S	136º 48′ 30.8″ E

Figure 13: Transmission paths for the six different ranges tested in Scenario 2. The transmitter was kept stationary, and the receiving location was moved along the road.

4. Results and Discussion

The two scenarios were entered into the various models and their results compared to the measured data. The results have been sorted by variables as each situation changes the outcome. This allows the best model to be selected for a given set of variables.

To test the validity of the models, near free space parameters (1000 m antenna heights) were entered and the results compared with those calculated using the free space equation. All programs came back with signal loss levels similar to those predicted by the free space equation. This indicates that the models are being interpreted correctly.

The total errors in the measured data are a result of the error of measurement for each component of the setup. For a setup containing two horn antennas, the error is made up of the error in the measured received power, measured transmitted power, estimated antenna gain for both transmitting and receiving antennas as well as the cable loss measured on a spectrum analyser. As this setup does not change, the error in all measurements made with this equipment is 2 dB which is one standard deviation assuming all errors follow a Gaussian distribution. Following the same process for a setup containing two helix antennas, the error in all measurements is 2.5 dB which is one standard deviation assuming all errors follow a Gaussian distribution. Error bars are not included on the plots as they will not be easily visible with the number of data points and scales used.

4.1 Scenario 1

The measured data was compared against the models described in Section 1.2 in several different ways. This allowed a greater understanding of which model would work best in a given situation. The models were tested to see how they varied against the measured data over frequency, range and transmitter height.

First the variation with frequency was analysed. This was done for each distance, polarisation and transmitter height. Figures 14, 15, and 16 shows the change in power loss as the range increases from 1.18 km to 3.06 km to 4.98 km. Both the polarisation and transmitter heights remain the same in these examples.

Scenario 1
R: 1.18 km, Pol: VxV, Tx Hgt: 8.93 m

Figure 14: Signal power loss over a range of 1.18 km for Scenario 1. The polarisation for both antennas was vertical and the transmitter height was 8.93 m. The plot shows how most of the data does not change much as the frequency increases. The error in measured data is 2 dB.

Scenario 1
R: 3.06 km, Pol: VxV, Tx Hgt: 8.93 m

Figure 15: Signal power loss over a range of 3.06 km for Scenario 1. The polarisation for both antennas was vertical and the transmitter height was 8.93 m. The plot shows how most of the data doesn't change much as the frequency increases. The error in measured data is 2 dB.

Scenario 1
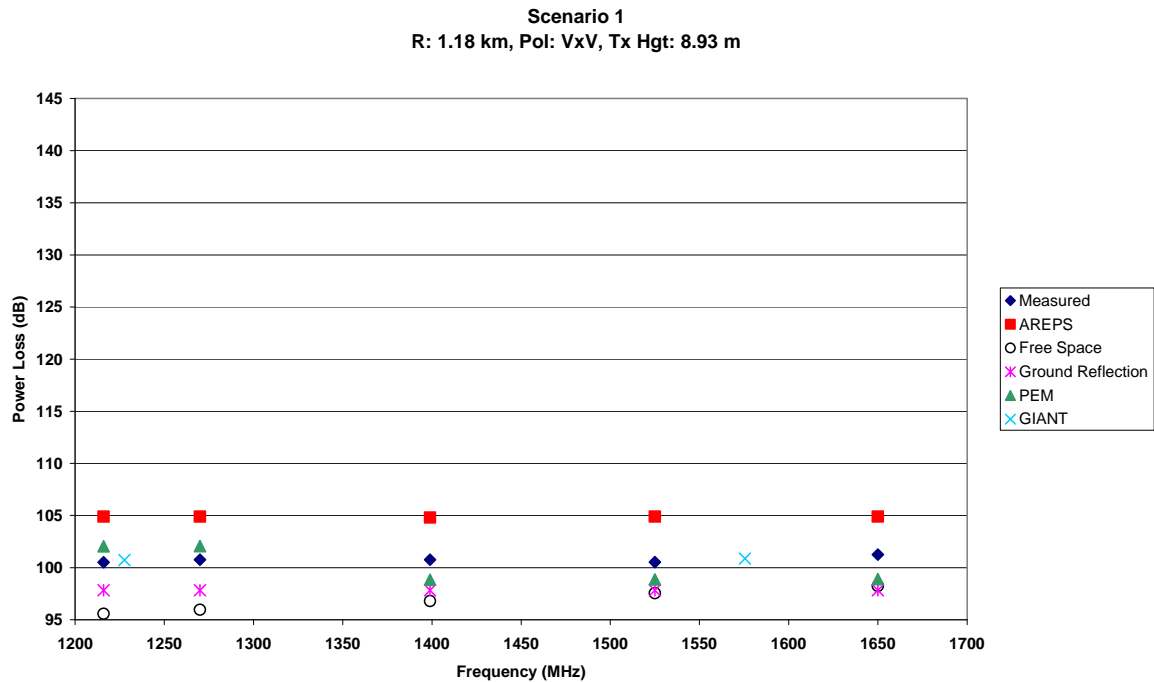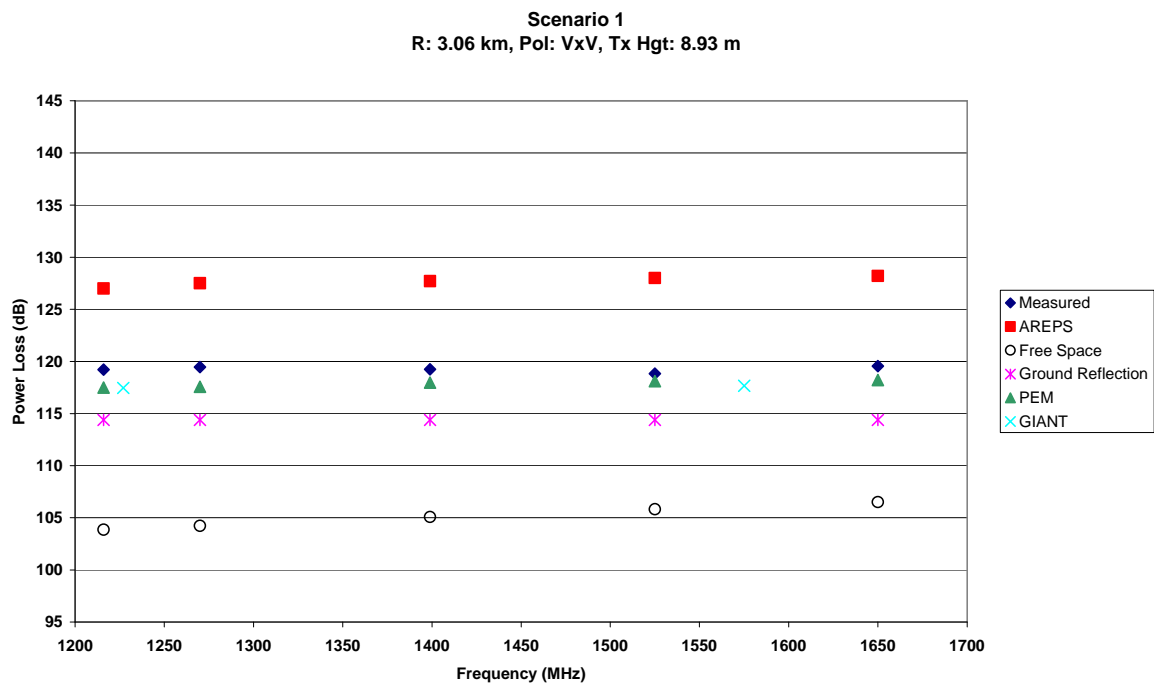**R: 4.98 km, Pol: VxV, Tx Hgt: 8.93 m**
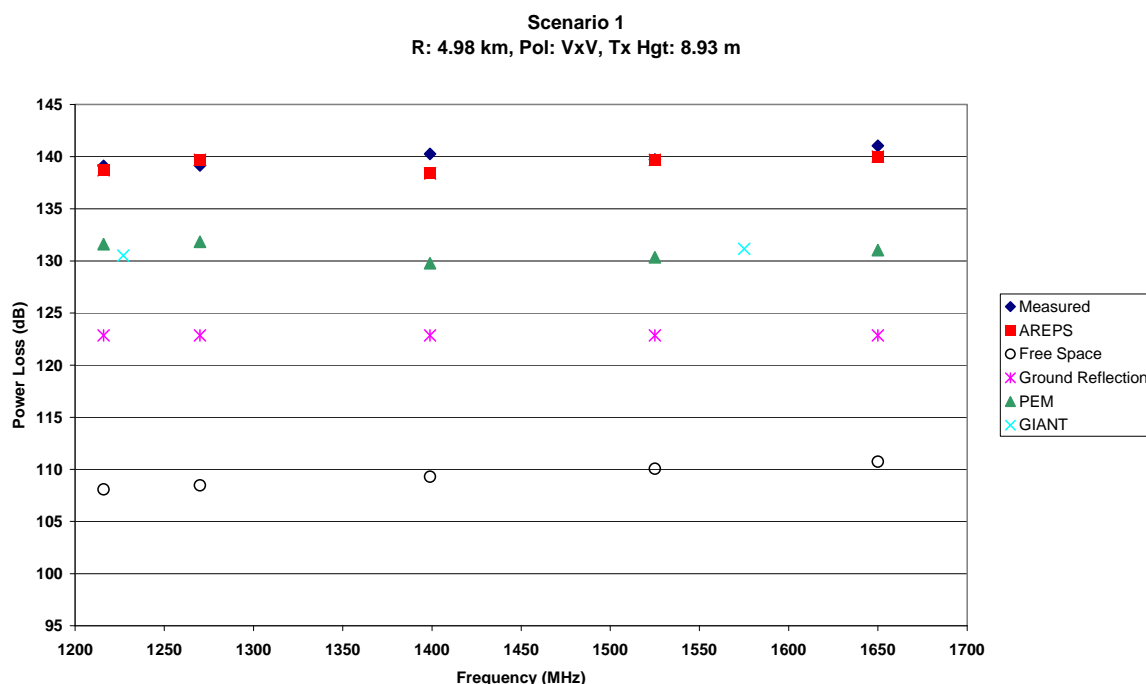
Figure 16: Signal power loss over a range of 4.98 km for Scenario 1. The polarisation for both antennas was vertical and the transmitter height was 8.93 m. The plot shows how most of the data does not change much as the frequency increases. Also note how the free space model is far underestimating the signal power loss compared to the measured data. The error in measured data is 2 dB.

When observing the plots shown above, it can be seen that the power loss does not fluctuate greatly over the frequencies tested. Both the measured and modelled data show this trait. Some of the models are frequency dependent, and others are not. Yet it appears that at these transmitter heights, polarisations and distances, a change in frequency from 1.2 to 1.65 GHz will not greatly affect signal propagation loss.

A more definitive method was needed over graphical representation to understand the difference between the models and measured data in each situation. The Root Mean Square (RMS) error value of the difference between the modelled data and the measured data was calculated for each set of variable combinations. The lower the RMS value, the closer the model is to the measured data. Tables 5, 6, and 7 show the corresponding RMS values for Figures 14, 15, and 16 as well as the values for other transmitter heights. The other polarisations were also calculated but are not shown here.

Table 5: RMS values across frequency for data shown in Figure 14. The range is 1.18 km, polarisation VxV and transmitter heights are 8.93 m, 6.13 m, and 3.43 m. The columns have been sorted in ascending order. This means the model with the lowest RMS value is the closest representation of the measured data for these variables. The error in these values is 2 dB.

RMS	
Tx Hgt	**8.93**
GIANT	0.07
PEM	1.79
GR	2.94
FS	4.03
AREPS	4.13

RMS	
Tx Hgt	**6.13**
GIANT	1.24
PEM	1.72
GR	2.34
AREPS	5.09
FS	6.64

RMS	
Tx Hgt	**3.43**
GR	1.50
PEM	1.52
GIANT	3.07
AREPS	6.17
FS	10.84

Table 6: RMS values across frequency for data shown in Figure 15. The range is 3.06 km, polarisation VxV and transmitter heights are 8.93 m, 6.13 m, and 3.43 m. The columns have been sorted in ascending order. This means the model with the lowest RMS value is the closest representation of the measured data for these variables. The error in these values is 2 dB.

RMS	
Tx Hgt	**8.93**
PEM	1.45
GIANT	1.70
GR	3.45
AREPS	8.43
FS	14.20

RMS	
Tx Hgt	**6.13**
PEM	2.09
GIANT	3.37
GR	5.49
AREPS	8.13
FS	18.06

RMS	
Tx Hgt	**3.43**
PEM	1.24
GIANT	4.43
AREPS	8.27
GR	12.77
FS	22.08

Table 7: RMS values across frequency for data shown in Figure 16. The range is 4.98 km, polarisation VxV and transmitter heights are 8.93 m, 6.13 m, and 3.43 m. The columns have been sorted in ascending order. This means the model with the lowest RMS value is the closest representation of the measured data for these variables. The error in these values is 2 dB.

RMS	
Tx Hgt	**8.93**
AREPS	1.00
GR	8.73
GIANT	9.03
PEM	9.03
FS	30.54

RMS	
Tx Hgt	**6.13**
AREPS	0.85
PEM	8.54
GIANT	11.25
GR	16.55
FS	33.34

RMS	
Tx Hgt	**3.43**
AREPS	0.70
PEM	8.51
GIANT	15.54
GR	24.66
FS	38.18

The tables are sorted in descending RMS values, allowing the best model for the situation to be at the top of the table. Although one model does not fit best for all situations, there does appear to be a relationship between the range and which model best fits the data. What is clear is that in all situations, the free space model is either at the bottom or close to the bottom of all tables. The free space model is not an accurate way to predict ground-to-ground power loss at Woomera regardless of the range, polarisation or transmitter height.

A variable more likely to affect signal power loss is the distance between transmitter and receiver. Figures 17, 18, 19, 20 and 21 show the difference between the measured data and each model individually across the ranges tested in this scenario. The polarisation in this set is

VxV and the transmitter height is 8.93 m across all plots. Other polarisations and transmitter heights were compared but aren't shown here.

Figure 17: Free space model (black) compared to the measured data (colour) for VxV polarisation and a transmitter height of 8.93 m. The plot shows how the measured and modelled data vary with distance at each frequency. The error in measured data is 2 dB.

Figure 18: Ground Reflection model compared to the measured data for VxV polarisation and a transmitter height of 8.93 m. The plot shows how the measured and modelled data vary with distance. The error in measured data is 2 dB.
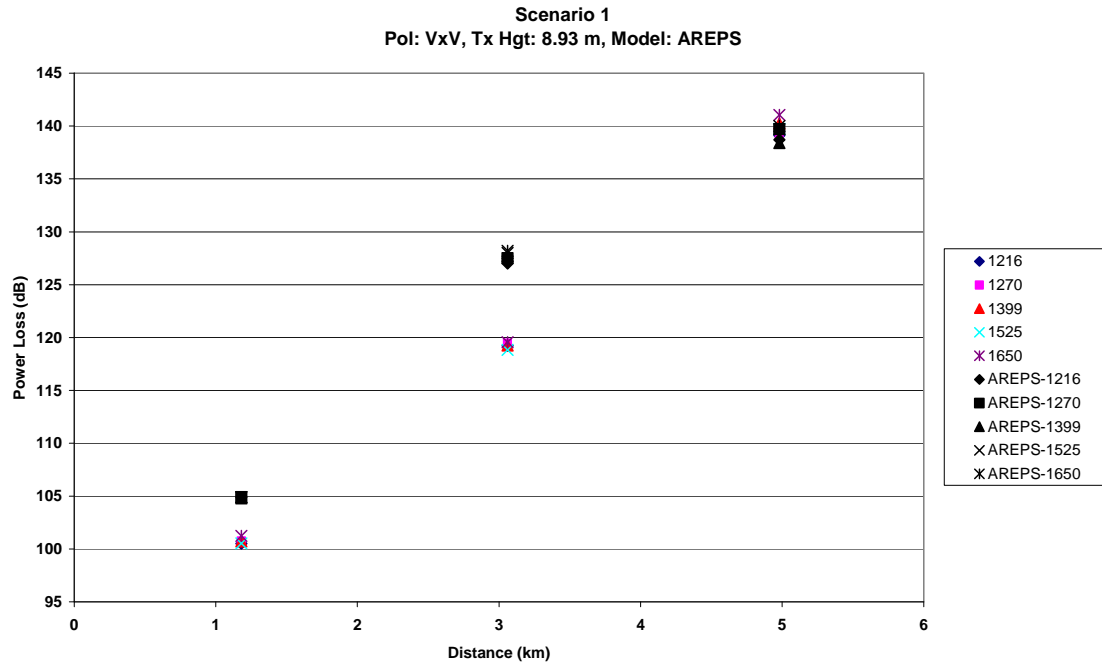
Figure 19: AREPS model compared to the measured data for VxV polarisation and a transmitter height of 8.93 m. The plot shows how the measured and modelled data vary with distance. The error in measured data is 2 dB.

Figure 20: PEM model compared to the measured data for VxV polarisation and a transmitter height of 8.93 m. The plot shows how the measured and modelled data vary with distance. The error in measured data is 2 dB.
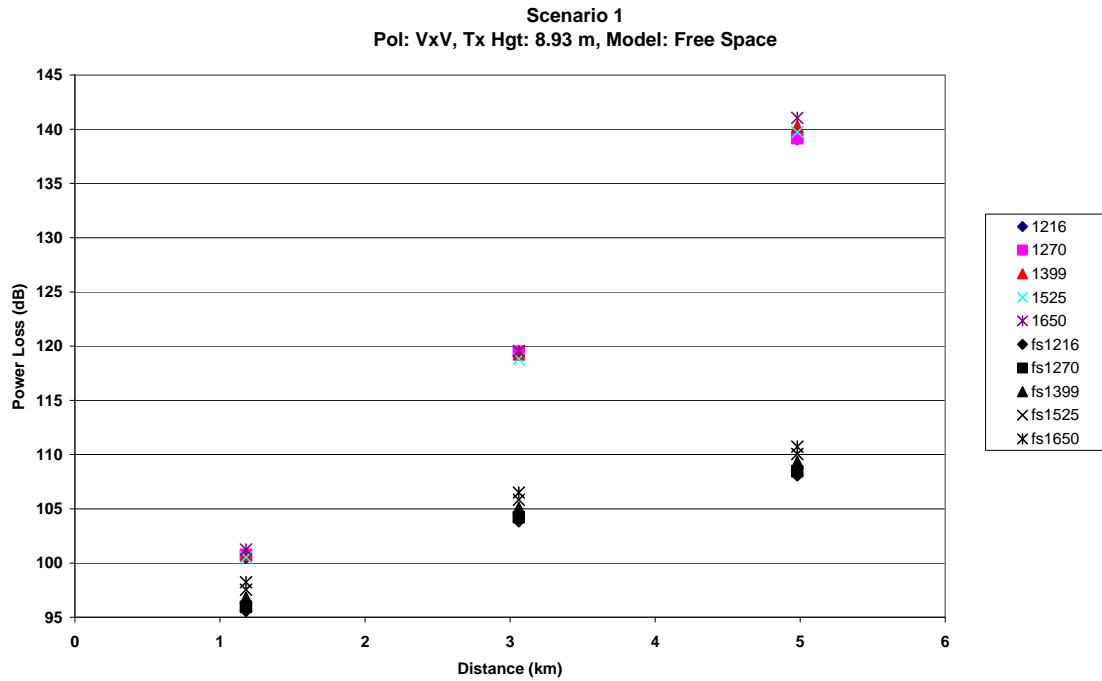

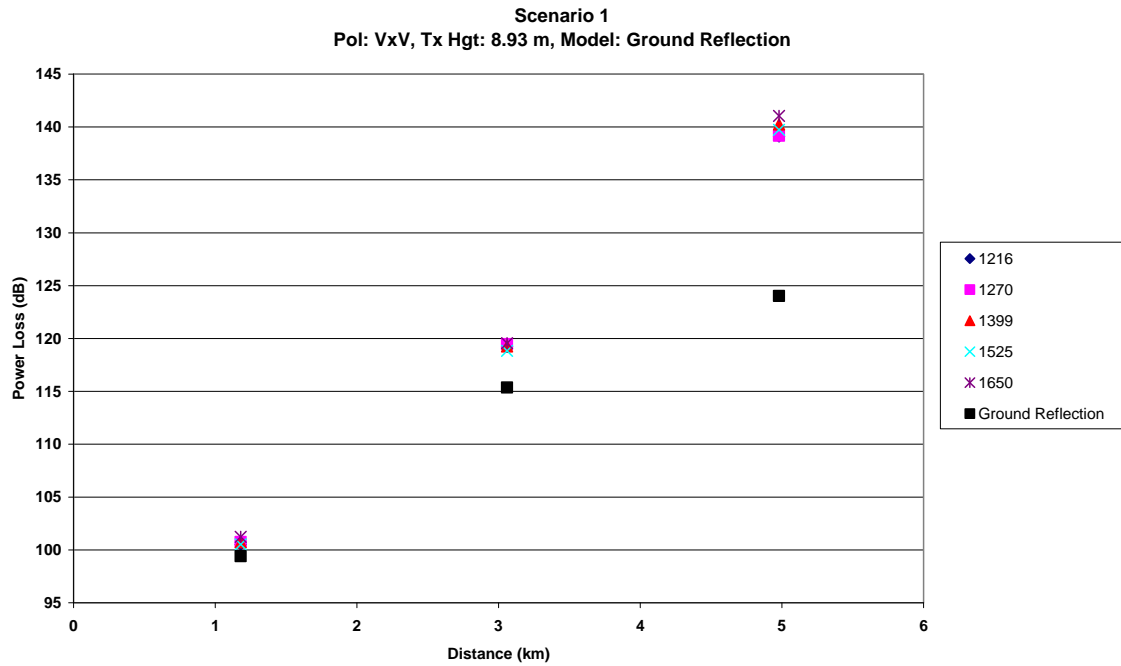*Figure 21: GIANT model compared to the measured data for VxV polarisation and a transmitter height of 8.93 m. The plot shows how the measured and modelled data vary with distance. The error in measured data is 2 dB.*
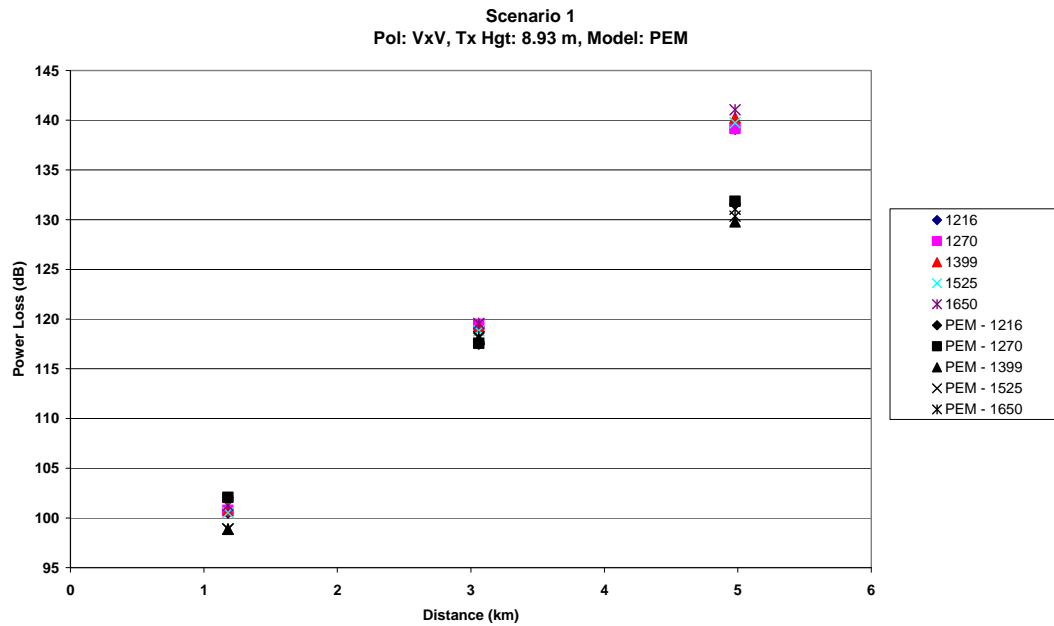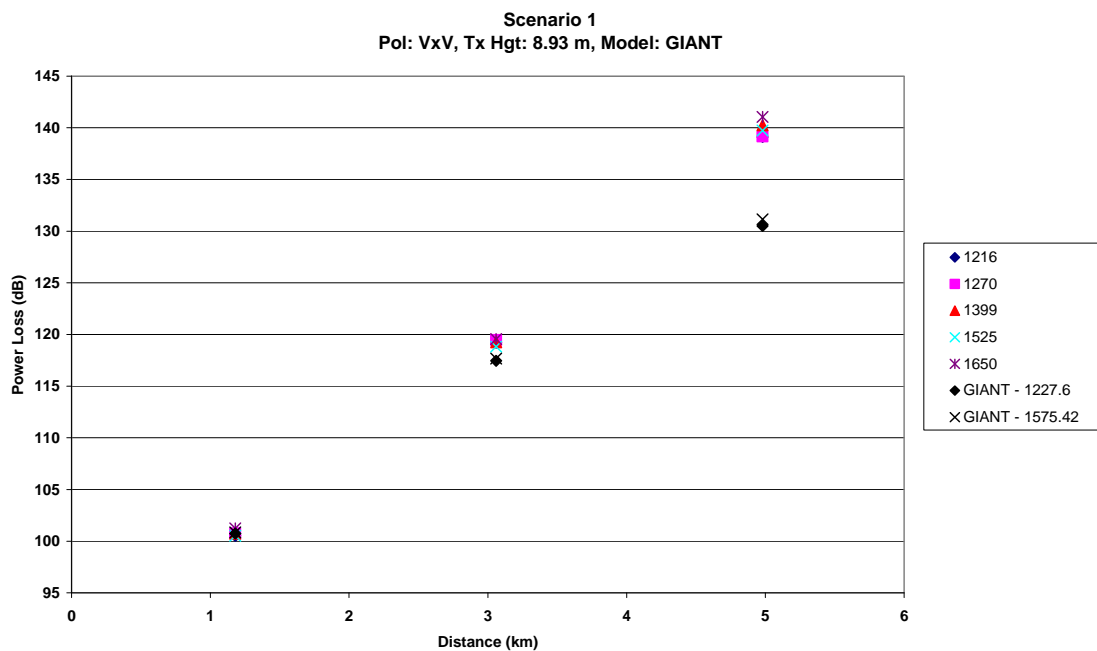
The different coloured lines are the different frequencies tested. Again it can be seen there is not a lot of difference between the frequencies. An interesting thing to observe is that the measured data is almost linear, whereas all the models have at least some curve.

Again to determine empirically which model was the closest to the measured data in each situation, the RMS values were calculated and sorted. Table 8 shows the RMS values for polarisation VxV and for each frequency. Only the values for transmitter height equal to 8.93 m are shown, other transmitter heights and polarisations were calculated but are not shown here. As GIANT was not set up to be able to test all 5 frequencies, only the GPS L1 and L2 frequencies were tested. These results have been added to the closest frequency column for comparison with the other data.

Table 8: RMS values for Figures 17 - 21. The transmitter height is 8.93 m, the polarisation is VxV and the data is sorted by frequency. The error in these values is 2 dB.

	RMS		RMS		RMS		RMS		RMS
	1216		**1270**		**1399**		**1525**		**1650**
PEM	4.53	**PEM**	4.43	**AREPS**	5.51	**GIANT**	5.11	**AREPS**	5.45
AREPS	5.17	**AREPS**	5.23	**GR**	5.86	**PEM**	5.52	**PEM**	5.99
GR	5.24	**GR**	5.26	**PEM**	6.20	**GR**	5.65	**GR**	6.31
GIANT	5.50	**FS**	19.98	**FS**	19.79	**AREPS**	5.86	**FS**	19.13
FS	20.19					**FS**	18.79		

The last variable that will affect the signal power loss is the transmitter height. Each set of tests were done at three transmitter heights. How the height of the radiating antenna affected the signal power loss is shown in Figure 22. Only one range and frequency is shown here (the approximate centre frequency) with all models displayed on one plot. Other combinations of frequency and range were examined but are not shown here.

Scenario 1
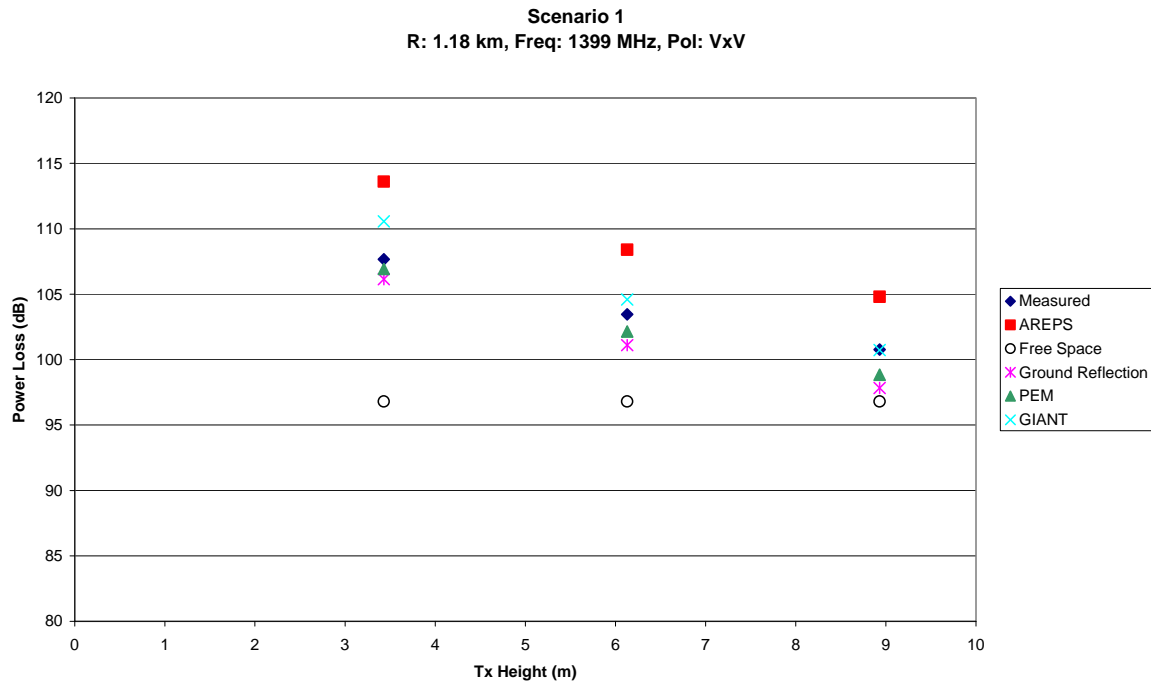**R: 1.18 km, Freq: 1399 MHz, Pol: VxV**

Figure 22: An example of how transmitter height effects signal power loss. This data is for a distance of 1.18 km, a frequency of 1399 MHz and a polarisation of VxV. The error in measured data is 2 dB.

The RMS values for each model compared to the measured data was calculated and tabulated. These results that correspond to Figure 22 were sorted and are shown in Table 9. Again only the L1 and L2 GPS frequencies were tested in GIANT.

Table 9: RMS values corresponding to Figure 22 for a distance of 1.18 km and polarisation of VxV. The data is sorted by frequency and ordered in ascending order of RMS value. The error in these values is 2 dB.

	RMS			RMS			RMS			RMS			RMS
	1216			**1270**			**1399**			**1525**			**1650**
GIANT	1.83		**PEM**	1.72		**PEM**	1.40		**PEM**	1.22		**PEM**	1.82
GR	2.01		**GR**	2.35		**GR**	2.34		**GIANT**	1.99		**GR**	2.77
PEM	2.09		**AREPS**	5.09		**AREPS**	5.03		**GR**	2.13		**AREPS**	4.81
AREPS	5.52		**FS**	8.56		**FS**	7.71		**AREPS**	5.48		**FS**	6.74
FS	8.51								**FS**	6.79			

It is difficult to determine which model is best for each situation as well as for an overall comparison due to so many variables. As such the occurrences of each model that had the lowest RMS for a given set of variables were calculated. In Table 10, the model and their occurrences in each set of variables is shown.

Table 10: Occurrences of each model having the lowest RMS value in a given set of variables. The left tables are how many times the model has been the closest fit, and the right table shows the percentage of the occurrence. The data is grouped by variable then the occurrences are tallied across all data. The error in these values is 2 dB.

Across Transmitter Height	
AREPS	38
GIANT	1
GR	5
PEM	16
FS	0
Total	60

Across Frequency	
AREPS	21
GIANT	6
GR	3
PEM	6
FS	0
Total	36

Across Range	
AREPS	49
GIANT	1
GR	0
PEM	10
FS	0
Total	60

Total		%
AREPS	108	69
GIANT	8	5
GR	8	5
PEM	32	21
FS	0	0
Total	156	100%

From Table 10, it can be seen that although the AREPS model does not always produce the lowest RMS value, it has the highest number of occurrences with it happening 69 % of the time. PEM is the second best all round model with it producing the lowest RMS value 21 % of the time.

On the other hand, the Free Space model never produced the lowest RMS value in any of the situations tested. In all cases, the free space model underestimated the power loss by as much as 67 dB. This is a clear indication that the free space model should not be used for calculating signal propagation loss in ground to ground transmissions.

In most cases, except for the close range tests, all the models underestimated the signal power loss when compared to the measured data. Free space underestimated it the most, and there was no clear pattern between the other models.

Further analysis was done to determine what the 95 % confidence interval is for each model. This establishes that 95 % of the time, the modelled data is within a given range of the measured data (shown in Table 11).

Table 11: The difference between measured and modelled data. The error in these values is 2 dB.

Model	95% of the time within….
AREPS	28 dB
PEM	36 dB
GIANT	37 dB
Ground Reflection	41 dB
Free Space	50 dB

This extra analysis again shows that AREPS is the better model amongst the others tested as it has the lowest difference with the measured data.

4.2   Scenario 2

Scenario 2 was designed to represent a soldier in the field with a handheld GPS receiver and an enemy soldier with a handheld jammer. This keeps the transmitter heights low and limits the polarisations used to just CxC (it is assumed that GPS jammers will use helix antennas).

The same analysis as Scenario 1 was carried out on the data collected from Scenario 2. The data was sorted into variables and the best model was determined via graphical and numerical means.

The modelled data was compared to the measured data to see how they varied across frequency. Figure 23 shows all the models compared with the measured data for a transmitter height of 2 m, polarisation of CxC and a range of 1.14 km. For comparison, Figure 24 shows the same comparison for a range of 18.7 km.

Scenario 2
R: 1.14 km, Pol: CxC, Rx Hgt: 2 m

Figure 23: Measured data compared to modelled data for a range of 1.14 km, polarisation of CxC and a receiver height of 2 m. It can be seen the data does not change much with frequency. The error in measured data is 2.5 dB.

Scenario 2
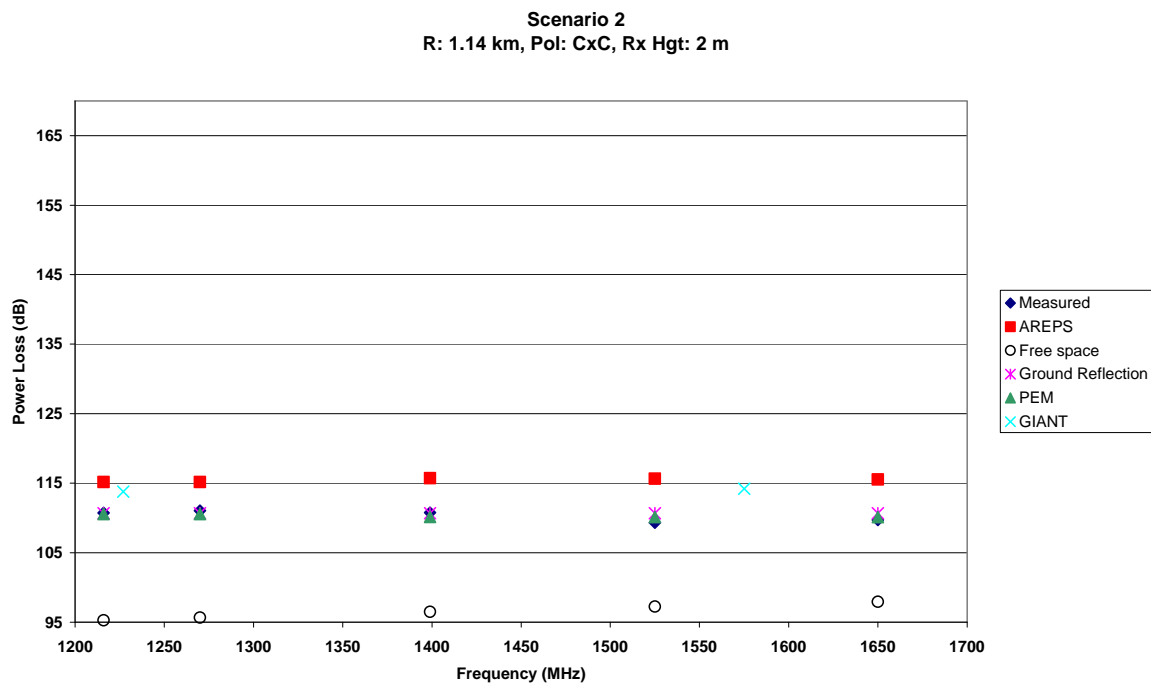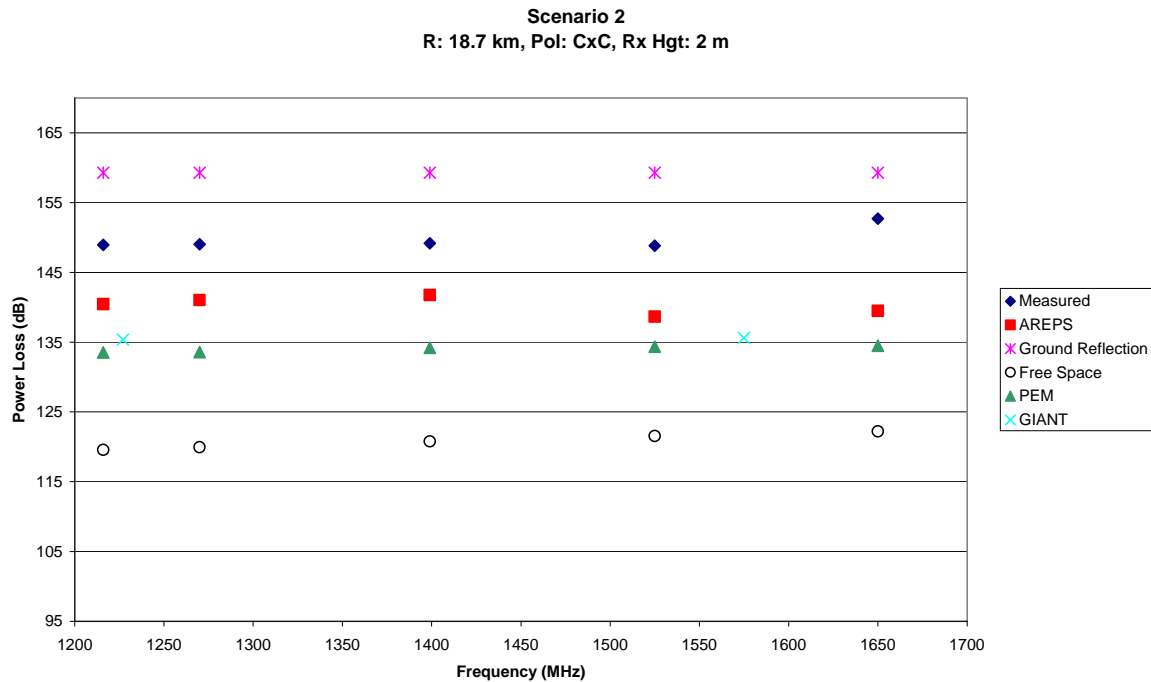**R: 18.7 km, Pol: CxC, Rx Hgt: 2 m**

Figure 24: Measured data compared to modelled data for a range of 18.7 km, polarisation of CxC and a receiver height of 2 m. It can be seen the data doesn't change much with frequency. The error in measured data is 2.5 dB.

Figure 23 shows that at a closer range, the difference between the models is not that great whereas in Figure 24 the modelled and measured data are quite spread out. In both figures it can be seen that, similarly to Scenario 1, the power loss does not vary by much across the frequencies tested.

As with Scenario 1, the RMS values for each model was calculated and sorted to determine which model best resembled the data for a given set of variables. Table 12 shows the RMS values for all distances in Scenario 2. For the data shown, the receiver height was 2 m. Other receiver heights were calculated but are not shown here.

Table 12: RMS values for Figures 23 and 24. Other ranges are included with the models sorted in ascending RMS values. Only the values for the receiver height of 2 m is shown here. The error in these values is 2.5 dB.

1.14 km

	2 m
PEM	0.54
GR	0.77
GIANT	3.69
AREPS	5.22
FS	13.87

2.99 km

	2 m
AREPS	1.44
PEM	2.05
GR	3.85
GIANT	8.15
FS	26.36

5.61 km

	2 m
PEM	1.07
GR	2.84
GIANT	4.54
AREPS	5.58
FS	25.20

9.62 km

	2 m
AREPS	1.44
GR	2.57
PEM	13.67
GIANT	17.04
FS	34.94

16.63 km

	2 m
GIANT	1.76
PEM	2.87
AREPS	10.21
FS	17.21
GR	20.32

18.7 km

	2 m
AREPS	9.67
GR	9.67
GIANT	14.23
PEM	15.74
FS	28.92

From Table 12 it can be seen that both AREPS and PEM are the more consistently accurate models for signal power loss across frequency.

Figures 25, 26, 27, 28 and 29 show the measured data against each individual model and how they compare across the ranges tested. The different colours in the plots indicate each frequency tested.

Scenario 2
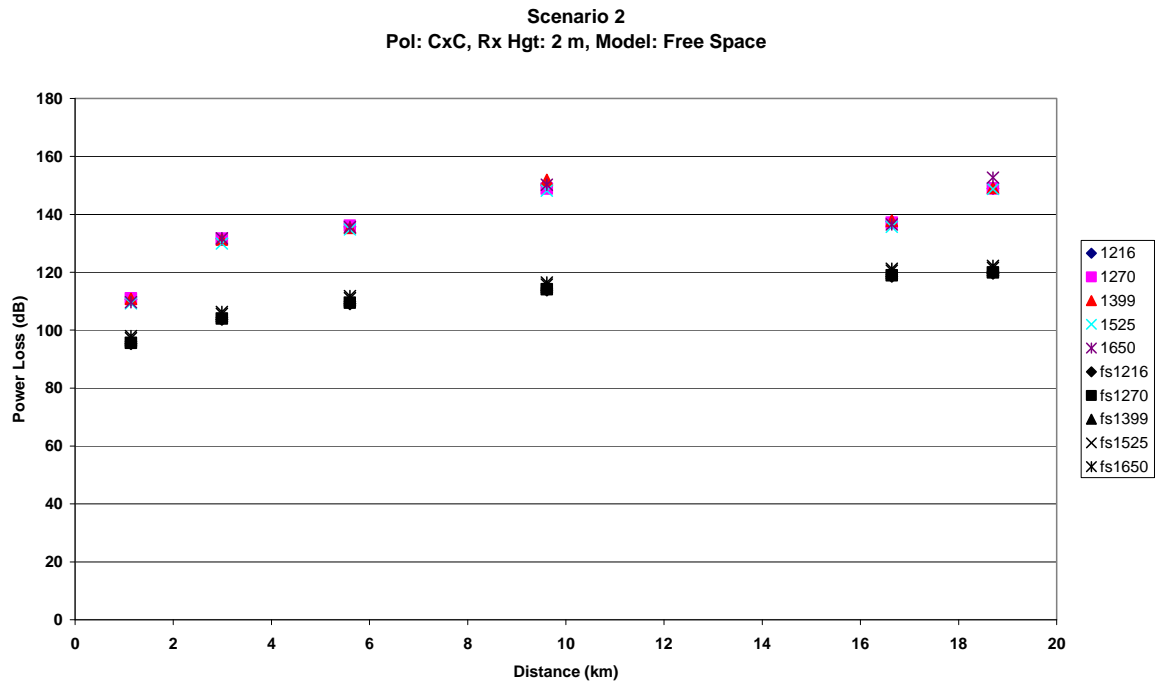**Pol: CxC, Rx Hgt: 2 m, Model: Free Space**

Figure 25: Free space model compared to the measured data for CxC polarisation and a receiver height of 2 m. The plot shows how the measured and modelled data vary with distance. The error in measured data is 2.5 dB.

Scenario 2
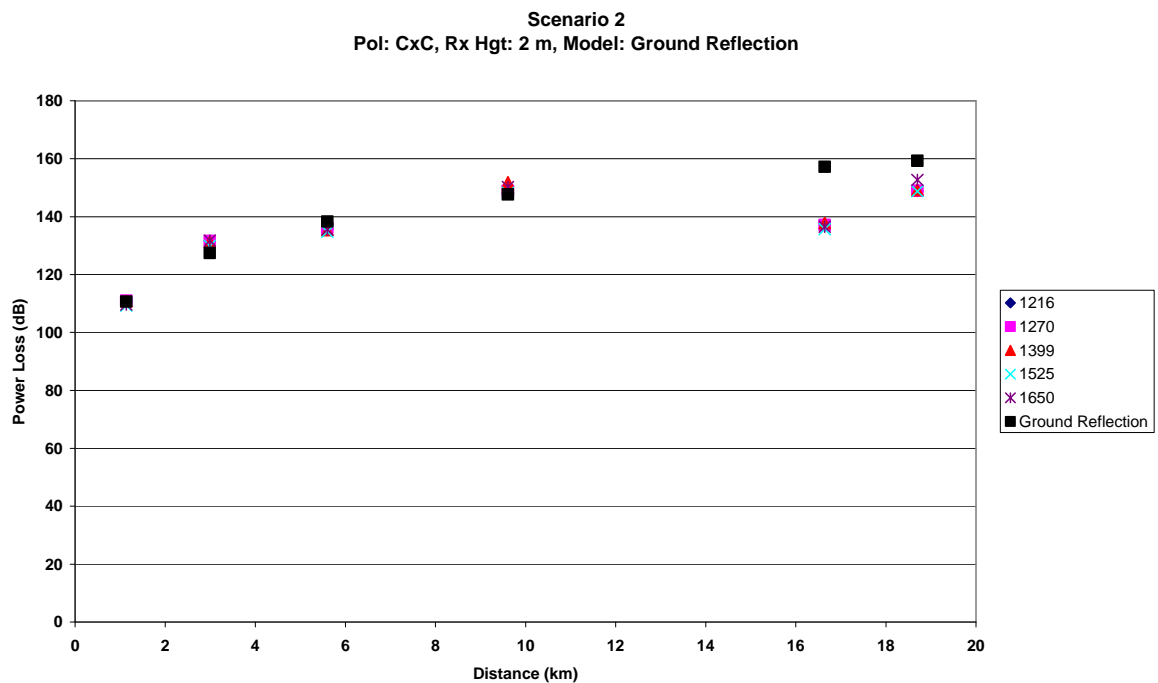**Pol: CxC, Rx Hgt: 2 m, Model: Ground Reflection**

Figure 26: Ground Reflection model compared to the measured data for CxC polarisation and a receiver height of 2 m. The plot shows how the measured and modelled data vary with distance. The error in measured data is 2.5 dB.

Scenario 2
Pol: CxC, Rx Hgt: 2 m, Model: AREPS
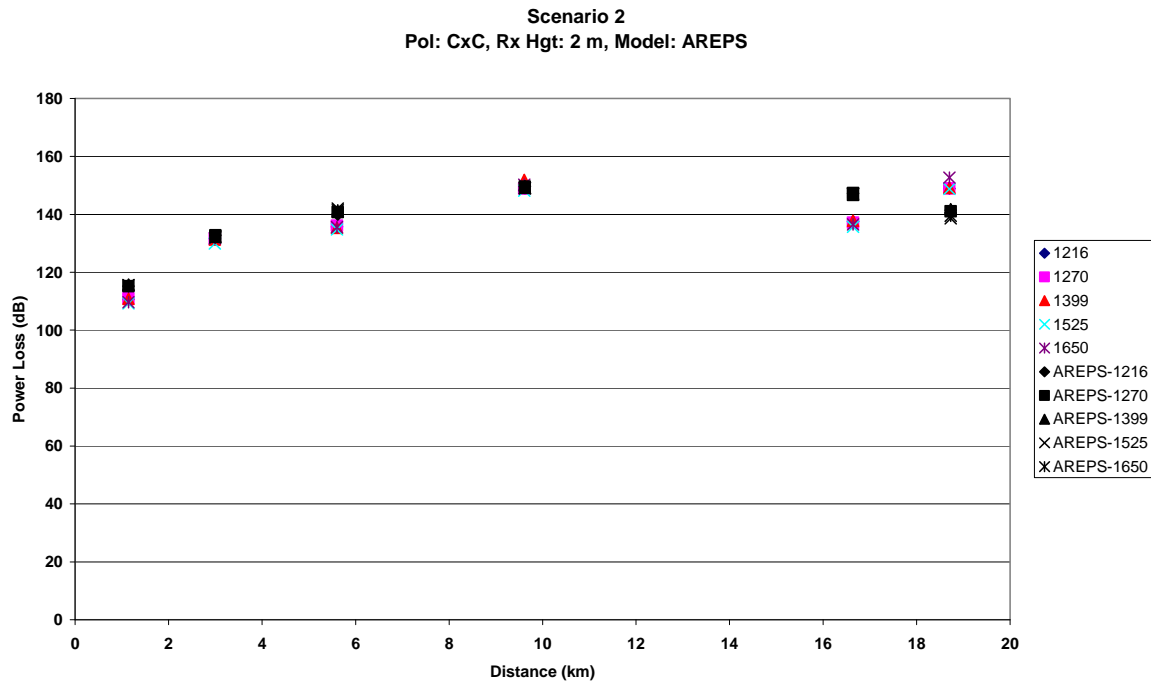
Figure 27: AREPS model compared to the measured data for CxC polarisation and a receiver height of 2 m. The plot shows how the measured and modelled data vary with distance. The error in measured data is 2.5 dB.

Scenario 2
Pol: CxC, Rx Hgt: 2 m, Model: PEM

Figure 28: PEM model compared to the measured data for CxC polarisation and a receiver height of 2 m. The plot shows how the measured and modelled data vary with distance. The error in measured data is 2.5 dB.

Scenario 2
Pol: CxC, Rx Hgt: 2 m, Model: GIANT

Figure 29: GIANT model compared to the measured data for CxC polarisation and a receiver height of 2 m. The plot shows how the measured and modelled data vary with distance. The error in measured data is 2.5 dB.
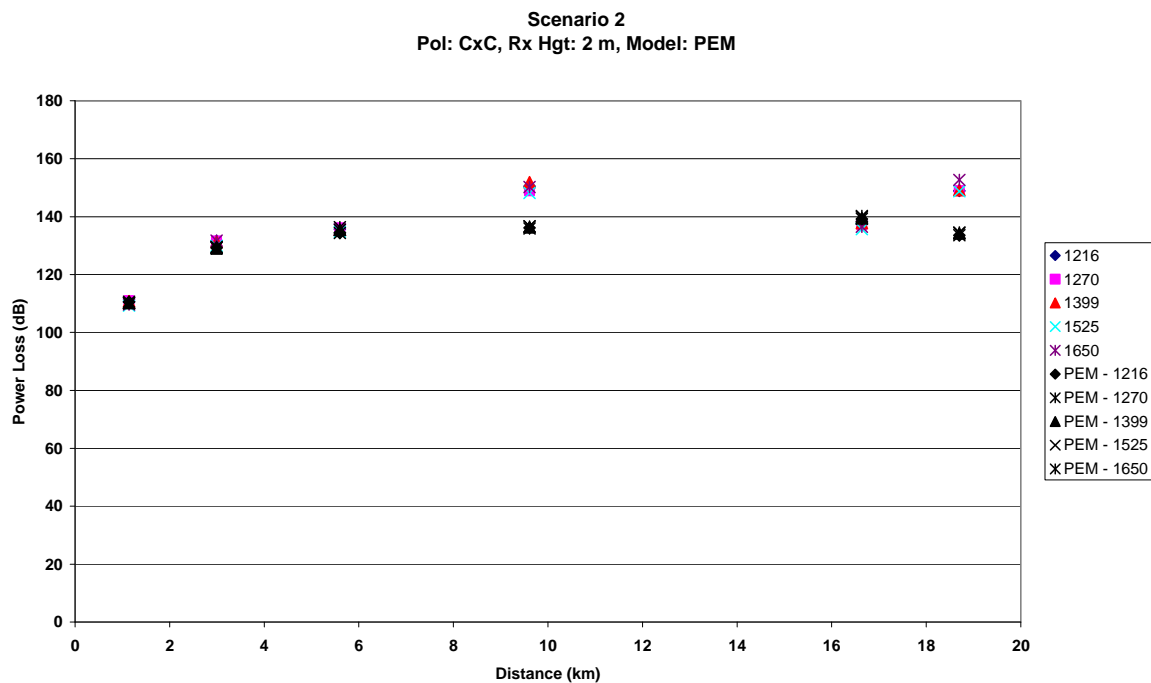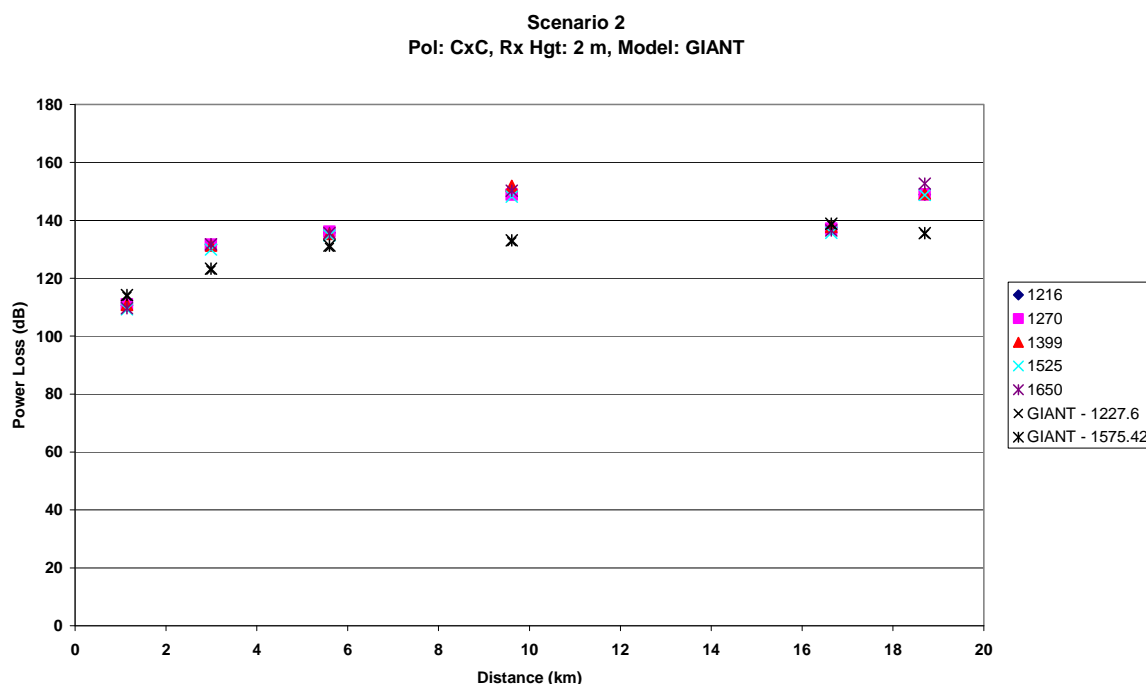
As for the results in Figures 23 and 24, it can be seen that there is not much variation in frequency across the ranges.

The models seem to not meet the measured data at the 18.73 km distance. This may be due to an error in the DTED data used in some of the models. The receiving location was on top of a hill with what appeared to be direct line of sight to the transmitter. However upon closer inspection of the DTED data, it shows this location to be slightly behind the above mentioned hill, which would affect the signal power levels received as it is no longer line of sight. This effect is also seen in the 3 m receiver height data.

The RMS values for the data across range for the 2 m receiver height are shown in Table 13. The RMS values were calculated for the other transmitter heights but are not shown here.

Table 13: RMS values for Figures 25 - 29. The values are for CxC polarisation and a receiver height of 2 m. The data is split into frequencies with each set ordered with ascending RMS value. The error in these values is 2.5 dB.

	1216
AREPS	5.85
PEM	8.69
GR	9.36
GIANT	9.82
FS	26.76

	1270
AREPS	5.91
PEM	8.35
GR	9.45
FS	26.09

	1399
AREPS	5.77
PEM	8.92
GR	9.32
FS	25.90

	1525
AREPS	7.40
PEM	7.74
GIANT	9.85
GR	9.96
FS	23.53

	1650
AREPS	7.71
GR	9.19
PEM	9.45
FS	24.68

The receiver height or the height of the soldier more specifically would affect the signal power loss. The data was analysed against receiver height and Figures 30 and 31 show the effect at 2.99 km and 18.7 km respectively. The other ranges were plotted but aren't shown here.
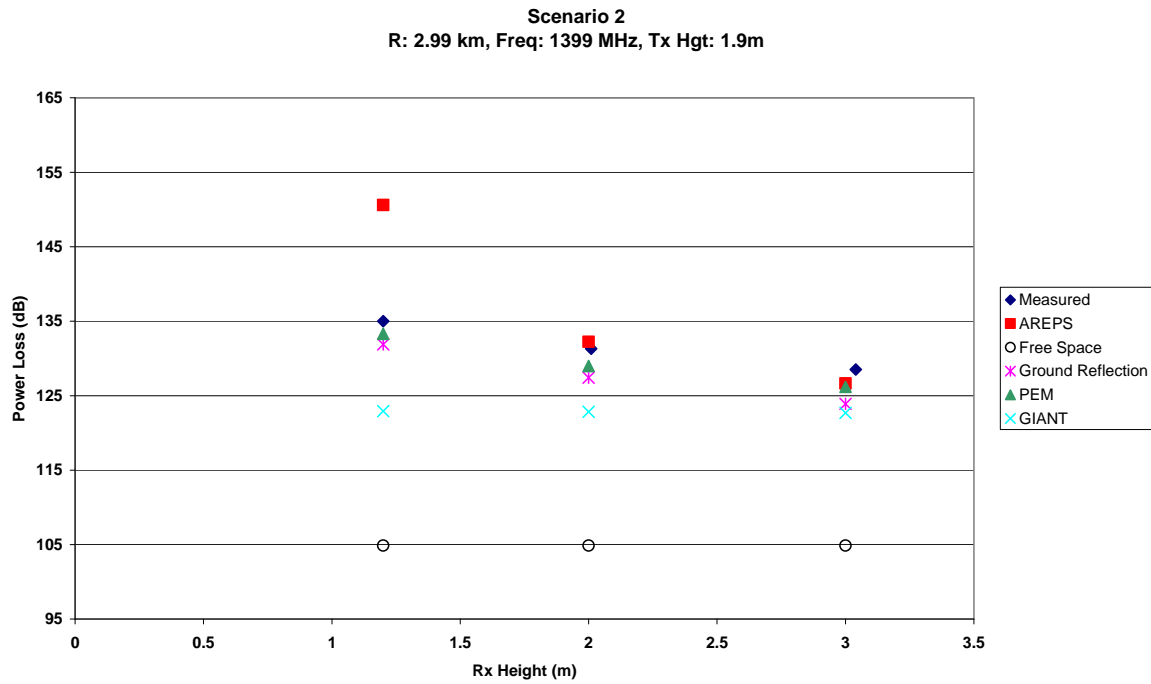

Figure 30: Measured data compared to modelled data for a distance of 2.99 km and a frequency of 1399 MHz. The plot shows how the receiver height affects the signal power loss over this distance. The error in measured data is 2.5 dB.
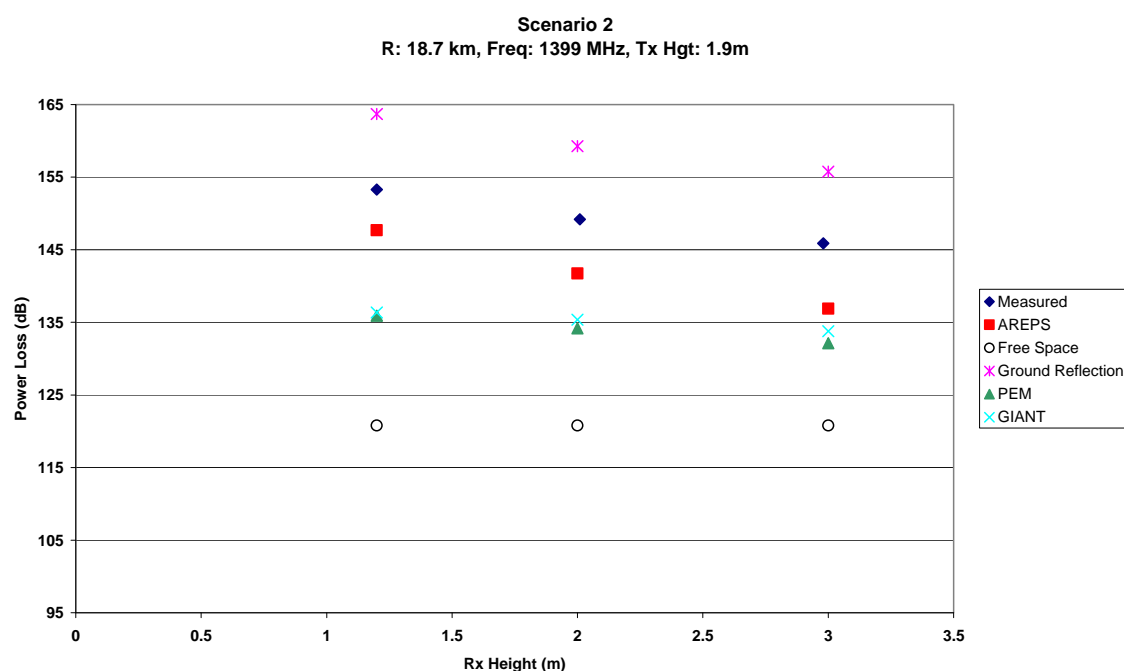
Figure 31: Measured data compared to modelled data for a distance of 18.7 km and a frequency of 1399 MHz. The plot shows how the receiver height affects the signal power loss over this distance. The error in measured data is 2.5 dB.

The RMS values for the corresponding data are shown in Tables 14 and 15. Again the values are sorted according to lowest RMS value indicating a closer match to the measured data.

Table 14: RMS values corresponding to Figure 30. The data is for a distance of 2.99 km. All frequencies tested are shown in this table. The RMS value reflects how well each model performs across a range of receiver heights. The error in these values is 2.5 dB.

	1216		1270		1399		1525		1650
PEM	3.19	PEM	2.92	PEM	2.13	PEM	0.66	PEM	2.24
GR	4.04	GR	4.13	GR	3.91	GR	2.75	GR	4.68
AREPS	9.01	AREPS	8.88	AREPS	9.08	GIANT	8.58	AREPS	9.90
GIANT	9.04	FS	27.94	FS	26.86	AREPS	10.35	FS	25.96
FS	28.16					FS	24.87		

Table 15: RMS values corresponding to Figure 31. The data is for a distance of 18.7 km. All frequencies tested are shown in this table. The RMS value reflects how well each model performs across a range of receiver heights. The error in these values is 2.5 dB.

	1216		1270		1399		1525		1650
AREPS	8.54	AREPS	8.15	AREPS	7.48	GR	9.27	GR	5.25
GR	10.15	GR	9.99	GR	10.12	AREPS	11.51	AREPS	15.09
GIANT	15.78	PEM	16.47	PEM	15.46	GIANT	15.53	PEM	20.48
PEM	16.35	FS	29.85	FS	28.83	PEM	16.40	FS	32.75
FS	30.05					FS	29.18		

It can be seen that the best model to represent the data changes with each set of variables. The occurrence of each model best representing the data in each section shown above was counted as well as across all sets of variables. The results are shown in Tables 16 and 17.

Table 16: Occurrences of each model having the lowest RMS value in a given set of variables. The right column is how many times the model has been the closest fit. The error in these values is 2.5 dB.

Across Range	
AREPS	13
GR	1
GIANT	0
PEM	1
FS	0
Total	15

Across Height	
AREPS	4
GR	11
GIANT	1
PEM	14
FS	0
Total	30

Across Frequency	
AREPS	6
GR	5
GIANT	2
PEM	5
FS	0
Total	18

Table 17: The number of occurrences of each model being the best fit over all the data in Scenario 2. The left column is how many times the model has been the closest fit, and the right column is a percentage of the occurrence. The error in these values is 2.5 dB

	Total	%
AREPS	23	37
GR	17	27
GIANT	3	4
PEM	20	32
FS	0	0
Total	63	100

It can be seen that again AREPS has the highest occurrence of best fitting the data with it occurring 37 % of the time. However, it is not as frequent as it was in Scenario 1 which had an occurrence of 69 %.

What is the same as Scenario 1 is that the Free Space model has never been the best fit to the measured data. In all cases, the free space model underestimated the power loss by up to 40 dB. This reinforces the idea that the Free Space model should not be used to estimate signal power loss in ground to ground transmissions.

Most models had mixed results compared to the measured data. Across the ranges tested most models overestimated for short ranges but underestimated for long ranges. There was no clear pattern as to what model would over/under estimate and where. However no model underestimated as much as the free space model, which underestimated the power loss continuously.

If a "back of the envelope" model is needed for ground-to-ground propagation loss at Woomera, it appears that the two-ray ground reflection model (fourth power law loss) is a reasonable choice, and is certainly far more accurate than the often used free-space propagation model.

The 95 % confidence interval was calculated for each model as was done in Scenario 1. Table 18 shows the 95 % confidence interval for each model.

Table 18: Difference between modelled and measured data. The error in these values is 2.5 dB.

Model	95% of the time within....
AREPS	16 dB
PEM	19 dB
GIANT	19 dB
Ground Reflection	21 dB
Free Space	38 dB

AREPS is the best model in Scenario two as it differs from the measured data the least. This is congruent with Scenario 1.

4.3 Overall

AREPS appears to be the best fitting model to both Scenario 1 and Scenario 2. Combining the data from both Scenarios, AREPS is the best fitting model 59.8 % of the time for all tests conducted. This is compared to the PEM model, which is the second best fitting model for both Scenario 1 and 2, and over all data it is best 23.7 % of the time.

This is confirmed with the overall calculation of the 95 % confidence interval for the models shown in Table 19.

Table 19: Difference between meausured and modelled data. The error in these values is 2.5 dB.

Model	95% of the time within....
AREPS	24 dB
PEM	32 dB
GIANT	34 dB
Ground Reflection	40 dB
Free Space	48 dB

In Scenario 2, the difference between AREPS and PEM is quite low, however in Scenario 1, and thus overall, the difference is quite high. It indicates that AREPS is the clear winner in the models tested. This does not mean it is the best model to use. There are many other models that have not been included in this analysis. Section 5 discusses the need to try the other models for both completeness and international cooperation.

5. Further Work

The creation of two Scenario types in this trial resulted in fewer data points for analysis. This affects the validity of any conclusions made. To combat this issue, a second trial would be wise to increase the number of data points.

A second trial in Woomera would focus on one Scenario type with the intention of obtaining many more data points at various distances. The number of variables would most likely be reduced to allow a more focussed approach. The polarisations would be limited to just circularly polarised transmissions and only the transmitter or receiver height will be adjusted. Due to the small changes in signal power loss over the range of frequencies used, the second trial would most likely only use one or two frequencies

It would also be useful if the receiver sites were in the same bearing direction from the transmitter for each distance. This would allow for the terrain to remain mostly the same in each test, with only the extra distance added on for comparison. Currently, all the receiving locations were in different directions with respect to the transmission site. This added an extra factor in the signal power loss.

During the analysis of this trial, it became clear that there are far more models dealing with signal propagation loss than have been included in this report (e.g. Signal Propagation, Loss, And Terrain (SPLAT) analysis tool, Egli Propagation model). In the future, it would be prudent to test some of these extra models to determine their usefulness. Some models are commercial and some are developed by the military or government agencies. As we often collaborate on trials with international agencies, it would be a good idea to become familiar with their modelling practices.

6. Conclusion

The results obtained from the trial at Woomera in August 2011 were split into two scenarios depending on the variables tested. The two scenarios were analysed separately due to their differences. For each scenario the best fitting model was determined and then the two scenarios were compared based on model performance.

Scenario 1 looked at varying transmitter heights, frequencies, polarisations and distances between transmitter and receiver. The data was grouped according to variables and a model was selected as the best fit due to its RMS value. The model that had the most occurrences of being the best fit across all variable groups was the AREPS model. This occurred 69 % of the time. 95 % of the time, AREPS values were within 28.3 dB of the measured data.

Scenario 2 looked at a more specific, soldier versus soldier situation. The transmitter height was stationary, and the receiver height varied to simulate ground operations. There was only one polarisation and the range of frequencies used in Scenario 1 was used again. The same data analysis approach for Scenario 1 was used with the result being that AREPS was the model with the most occurrences of being the best fit. This occurred 37 % of the time. 95 % of the time AREPS values were within 15.61 dB of the measured data.

Combining both scenarios, AREPS was the best fit 60 % of the time. 95 % of the time AREPS was within 22 - 26 dB of the measured data. The model with the second highest occurrences of being the best fit was the PEM model. This occurred 21 % in Scenario 1, 32 % in Scenario 2 and

24 % overall. The 95 % confidence intervals for the PEM model were 34 - 38 dB in Scenario 1, 17 - 21 dB in Scenario 2 and 30 - 34 dB overall.

The Free Space model which is usually the 'back of the envelope' calculation was never the best fit for the data. This model underestimated the measured power loss in all tests done by as much as 65 - 69 dB. This model underestimated the power loss least at closer range and higher transmitter heights. However, the results indicate that if a back of the envelope calculation is required, the two-ray ground reflection model is a much better choice than free-space, although it still appears to consistently underestimate ground-to-ground propagation losses.

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19. ABSTRACT

This investigation aims to determine how ground to ground L-Band signals propagated in the Woomera region behave, as well as which propagation model best represents measured results.

The results were split into two scenarios depending on the variables tested. The two scenarios were analysed separately due to their differences in equipment setup. For each scenario the best fitting model was determined and then the two scenarios would be compared based on model performance.

Overall, the Advanced Refractive Effects Prediction System (AREPS) was the best fit 60 % of the time. The modelled propagation loss was within 22 - 26 dB of the measured value 95 % of the time. The Free Space model which is usually the 'back of the envelope' calculation was never the best fit for the data. However, the results indicate that if a back of the envelope calculation is required, the two-ray ground reflection model is a much better choice than Free Space, although it still appears to consistently underestimate ground-to-ground propagation losses.